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The effect of spindle perturbations on the quality of precision grinding*

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Introduction

In grinding, there are many perturbations to the spindle that degrade the quality of the workpiece surface being ground. Imbalance of the grinding wheel and runout of the wheel are two examples of such perturbations. These disturbances manifest themselves as varying system forces or varying system displacements. The dynamics describing the combination of machinery and material removal process then determine how these perturbations affect the process, for example, the grinding force or grinding depth of cut. The system output is given in terms of the degradation in quality of the workpiece surface. It is only in the context of the whole system, as shown in Figure 1, that the effect of poor wheel balance and poor wheel truing on workpiece quality can be assessed.

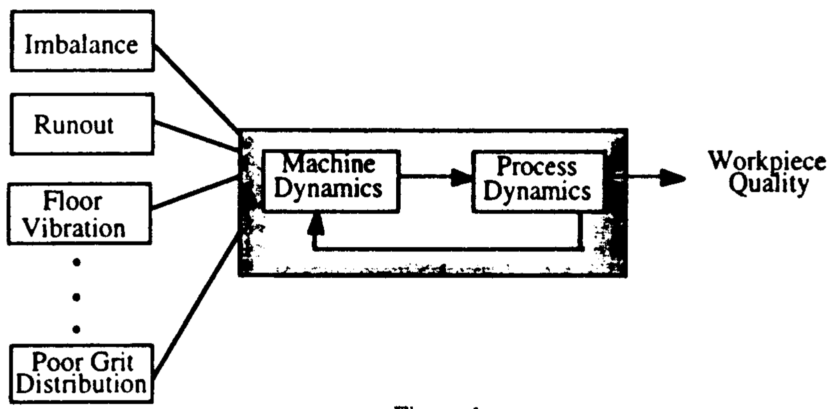

Figure 1.

Error sources (Input)

Sources of disturbances to an air-bearing spindle's axis of rotation are generally lumped into two categories, those which occur synchronously with the rotation, and those which are characterized as asynchronous. This categorization best applies to a disturbance whose frequency is at or above the fundamental frequency of the spindle, particularly in a highly repeatable air-bearing spindle. The asynchronous errors are associated with surface roughness of a ground part, and synchronous errors at the spindle rotational frequency may, depending on the relative rotational velocity of the workpiece and the wheel, manifest themselves as waviness or also as roughness in the workpiece.

In addition to the disturbances discussed above, there are subharmonic disturbances to the axis-of-rotation that usually show up as waviness, contour, or size error in the workpiece. These disturbances may be slowly varying, as for example, thermal drift of the spindle's axis, or much quicker disturbances like that induced by a change in spindle speed. In addition, for a rolling-element bearing, there are subharmonic disturbances associated with, for example, the cage pass frequency.

There are also other contributors that are not direct perturbations of the axis of rotation, but are perturbations of the material removal process and therefore indirectly of the axis of rotation. Consider, for example, that the grit is not evenly distributed around the wheel. This will have the

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effect of varying the normal and tangential forces associated with material removal and will consequently affect the axis of rotation depending on the machine dynamics.

These error contributors all affect the spindle axis of rotation in one way or another and they are coupled through the system dynamics model derived below. The simplified case discussed here involves the use of a high quality, air-bearing spindle where imbalance and runout become the dominant contributors to the synchronous, once-per-revolution spindle error motion. Surface finish due to asynchronous spindle error motion, and subharmonic effects will not be included in this analysis.

System Dynamics (transfer function)

In order to couple the error sources and to assess their effects on the workpiece surface, a model of the structural dynamics of the machine tool and the workpiece-tool interaction is derived with enough degrees of freedom to accurately represent the relevant parameters in the study of imbalance and runout. These parameters include the masses of the rotating spindles, the compliances between the spindles and ground, damping within the system, and the force due to infeed rate.

For cylindrical grinding, the unidirectional model illustrated in Figure 2 is driven with both an oscillating imbalance force and a runout displacement, to observe the relative effects of each. These error sources are coupled and phase-shifted to show the effects of combined imbalance and runout in the wheel. The effects of the imbalance and runout on the surface profile are observed through the material removal model. In this way, the effect of imbalance may be separated from the effect of runout as error sources.

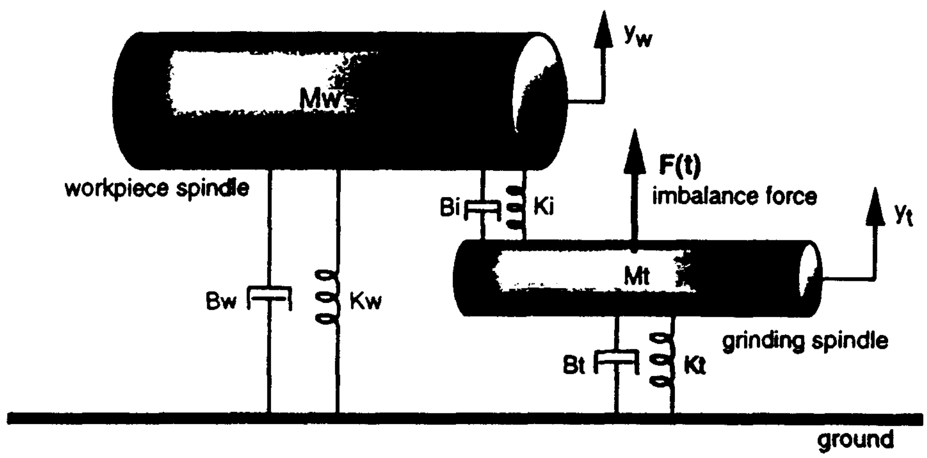

Figure 2.

In addition to investigating the effect of imbalance versus runout, the model is used to examine the importance of other system parameters with regard to imbalance in the grinding spindle. We show the effect of imbalance on cutting force while varying damping of the cutting process, that is, the damping between the grinding wheel and the workpiece. We also vary compliances in the system and observe how imbalance changes the cutting force with these new parameter values. In addition, the model simulates the synchronous loss of contact between the grinding wheel and the workpiece, reflecting, for example, a "low spot" on the grinding wheel.

The model is constructed classically, using ordinary differential equations and simulated with MATLAB and SIMULINK integration routines for stiff systems.

Workpiece Quality (Output)

The grinding performance is a combination of workpiece surface quality and cost (material removal rate, g-ratio, etc.). Surface errors are traditionally broken down into roughness, waviness, contour error, and subsurface damage. The waviness length of the once-per-revolution feed is the most sensitive category of workpiece error to imbalance and runout of the grinding wheel.

Simulation and Experimental Corroboration

The simulations performed were to address a number of fundamental questions. First, on what basis can runout and imbalance be compared, that is, what level of imbalance yields the same degradation of workpiece quality as a given level of runout? A basis for comparison is the variation in normal grinding force; when a given runout causes a grinding force variation equal to that caused by a given imbalance, their degradation of workpiece surface quality is equivalent. Analytically then, the dynamics of the interface between the wheel and workpiece determine the equivalency of imbalance and runout.

Second, given an allowable workpiece waviness, what levels of runout and imbalance are tolerable? This is determined both analytically and empirically and is similar to the approach used by Trmal and Kaliszer[1] who specified that the peak-to-valley amplitude of the waviness component introduced in the workpiece from imbalance should be less than 1/7 of the peak-to-valley height of the specified surface profile.

Third, how successfully can the deleterious effects of wheel runout be compensated by using imbalance which, at a given speed, yields an out-of-phase force in the direction normal to the workpiece surface? This compensates a sinusoidal time-varying force (due to runout) with a rotating force of constant magnitude (due to imbalance). Note that only the once-per-revolution component of runout can be compensated. This is accomplished by performing the balancing during grinding instead of in preparation for grinding. The accelerometer, which is arranged in the direction normal to the surface, will measure the sum of the accelerations due to imbalance and runout. Alternatively, this can be accomplished by using a dynamometer that measures the grinding force component normal to the surface.

Our experimental setup consists of an air spindle mounted on an isolated granite table. The spindle is imbalanced during operation and a spindle analyzer is used to determine axial and radial error motions of the spindle. A force dynamometer is mounted between the spindle and the table to measure forces generated by the imbalanced spindle in three directions. The spindle is configured for a peripheral grinding wheel and a linear table that feeds the work spindle into the grinding wheel. Surface finish on the workpiece is examined with a contacting profilometer. Compliance within the spindle is varied by changing the air supply pressure. This setup is particularly configured to explore the coupling of imbalance with a controlled compliance in the structure. This allows a "clean" experiment for corroborating the simple model of the system dynamics. Other elements of the experimental setup can also be changed, for example, by changing the wheel and workpiece materials, but such a change has a far ranging effect on many of the system parameters.

Conclusions

Considering perturbations to the grinding spindle along with the machine and process dynamics allows the effects of imbalance to be directly compared to wheel runout in terms of degradation of the workpiece surface caused by each. In addition, this leads to a rational method for specifying the quality of balance and runout that are required for a particular grinding operation to achieve a given workpiece surface quality. A different performance index is proposed to achieve higher quality grinding, that of minimizing the force perturbations to the grinding process rather than the force perturbations to the machine. This is tantamount to partially compensating once-per-revolution wheel runout with wheel imbalance.

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[1] G Trmal and H Kaliszer, "Some Aspects of Unbalance in the Wheel-Spindle Assembly of Cylindrical Grinding Machines," Annals of the CIRP, 21/1/1977, pp89-90.